SAIC-97/1033:APPAT-184

"STUDIES OF PLASMA FLOW PAST JUPITER'S SATELLITE IO"

PROGRESS REPORT: SECOND YEAR

(2/07/96—2/06/97)

Science Applications International Corporation

An Employee-Owned Company

NASA CONTRACT: NASW-4941

SPACE PHYSICS SUPPORTING RESEARCH AND TECHNOLOGY (SR&T),

AND SUBORBITAL PROGRAM

PRINCIPAL INVESTIGATOR:

JON A. LINKER

SCIENCE APPLICATIONS INTERNATIONAL CORPORATION

10260 CAMPUS POINT DRIVE

SAN DIEGO, CA 92121-1578

Studies of Plasma Flow Past Jupiter's Satellite Io

P.I.: Jon Linker

Progress Report: Second Year (2/07/96-2/06/97)

Introduction

Here we describe progress performed under Contract NASW-4941, awarded to Science Applications International Corporation, San Diego, for the period 2/07/96 to 2/06/97. Under this contract, we have investigated the interaction of Io, Jupiter's innermost Galilean satellite, with the Io plasma torus, and the interaction of Ganymede with the corotating Jovian plasma.

With the successful insertion of the Galileo spacecraft into orbit around Jupiter, many new observations have been made of the Jovian magnetosphere. Some of the most exciting results thus far have been in regards to Jupiter's satellites, Io and Ganymede. In both cases the large perturbations to the background (Jovian) magnetic field have been consistent with the satellites' possession of an intrinsic magnetic field. The gravity measurements implying a differentiated core at both Io and Ganymede (Anderson et al. 1996; Schubert et al. 1996) makes internal generation of a magnetic field by dynamo action in these satellites plausible, and, in the case of Ganymede, the identification of an intrinsic field is apparently unambiguous (Gurnett et al. 1996b; Kivelson et al., 1996c). For Io the situation is less clear, and further analysis is necessary to answer this important question.

During the past year, we have used time-dependent three-dimensional magnetohydrodynamic (MHD) simulations to study these plasma-moon interactions. The results from these simulations have been used directly in the analysis of the Galileo magnetometer data (Kivelson et al. 1996ab; Linker et al 1996ab). Our primary emphasis has been on the Io interaction, but we recently presented results on the Ganymede interaction as well (Linker et al. 1996c). In this progress summary we describe our efforts on these problems to date.

Progress Summary

(a) Initial Comparison of Conducting and Magnetized Models with Galileo Data

Prior to the Galileo spacecraft's flyby past Io, an unmagnetized Io with a conducting ionosphere was the predominant paradigm for describing Io's perturbation of the Jovian magnetic field. However, the possibility of an intrinsic magnetic field at Io was not ruled out by observations. The nature of Io's interaction with the plasma torus in the event Io is magnetized had been discussed (Neubauer 1978; Kivelson et al. 1979; Southwood et al. 1980), but detailed models had not been attempted. Our NASA support has allowed us to develop MHD computations for both the case of an unmagnetized, conducting Io and an Io possessing an intrinsic magnetic field (Linker 1995). Figure 1 shows an example of tracings of the magnetic field for a typical conducting model and a magnetized model. One sees similar magnetic topology and the presence of an Alfvén wing in both cases. The main difference is the more pronounced curvature of the field lines inward toward Io in the magnetized case. Prior to the flyby, we also carried out simulations with other dipole orientations at Io. Our primary goal at that time was to use the calculations in conjunction with Galileo data to place an upper limit on any Ionian magnetic moment.

The Galileo spacecraft flew by Io on December 7, 1995, with a closest approach distance of 898 km. The complete particles and fields data was not available until June, 1996, but survey magnetic field data (1 minute averages) were returned in late December, 1995. It was immediately clear that the large drop observed in the magnitude of the magnetic field ($\approx$ 40%) was much greater than that expected from previous computations for a conducting Io (Wolf-Gladrow et al. 1987; Linker et al. 1988; Linker et al. 1991), and in fact were most easily reconciled with a magnetized model for Io. Figure 2 shows the Galileo data in the "phi" coordinate system, where $\hat{x}$ is along the corotation direction, $\hat{y} = -\hat{b}\times\hat{x}$ (where $\hat{b}$ is a unit vector in the direction of the background field), and $\hat{z} = \hat{x} \times \hat{y}$ completes the right-hand system. Figure 2 shows that in this coordinate system, the background (Jovian)

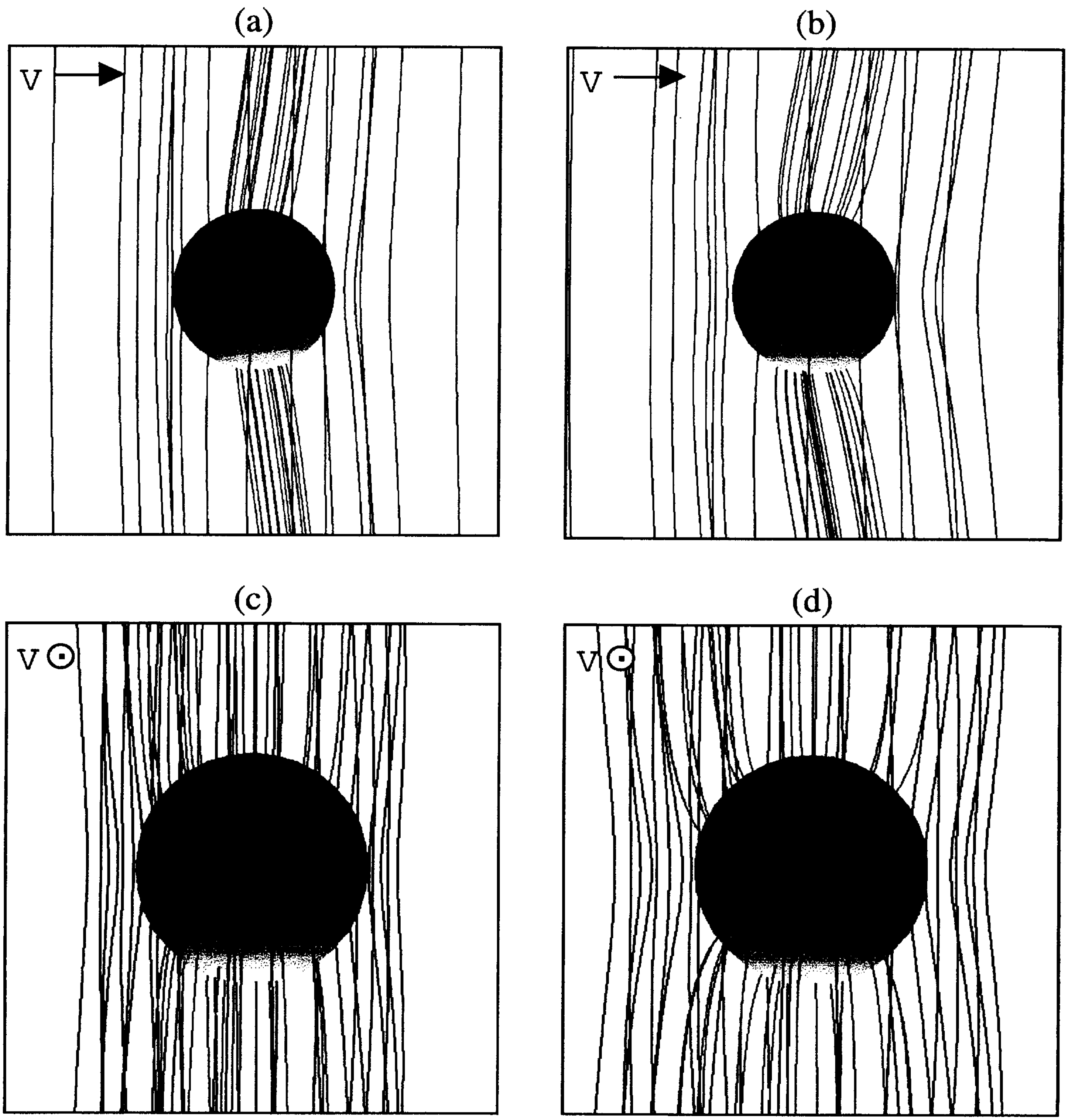

Figure 1. A comparison of magnetic field line tracings for a conducting and magnetized model of Io. (a) and (c) show the conducting model; (b) and (d) the magnetized model. (a) and (b) show a view looking towards Jupiter; (c) and (d) show a closeup view from downstream of Io. The tilt of the field in (a) and (b) is from the formation of Alfven wings. The overall topology of the field is similar in both the conducting and magnetized case, but the field is more strongly curved towards Io in the magnetized case.

magnetic field is almost entirely in the $-z$ direction, and that a large perturbation to the magnitude of $\vec{B}$ occurred at the Io flyby (closest approach was at 17:45:58 UT).

To directly compare our MHD simulations with the Galileo observations, we extracted data from the simulations along the Galileo trajectory to yield "simulated" flyby data. Figure 3 shows a comparison of these simulated flybys with the Galileo data of Figure 2. To appropriately normalize the comparison, the fractional perturbation to the background magnetic field is plotted. Figure 3(a) shows results typical of conducting models developed prior to the flyby: Io's ionosphere is assumed to be confined to near Io's surface, and the primary currents are assumed to be driven in the ionosphere (as opposed to pickup currents created via ionization or charge exchange). The perturbations to the magnetic field are in the right sense but the magnitude of the B_z perturbation is far too weak. This is true even if the conductivity for Io is chosen near infinity. The only ionospheric model that matches the B_z perturbation is shown in Figure 3(b); in this model Io's ionosphere (i.e., the region where the ion-neutral collision frequency approaches the ion gyro-frequency) extends out to 1.4 R_{Io}. This model would imply a neutral density $> 10^9$ at 900 km above Io's surface, and is contrary to expectations from atmospheric models (Strobel et al. 1994) and Io exosphere observations (Schneider et al. 1991).

Figure 3(c) shows the comparison for a magnetized Io. This model matches the strength of the B_z perturbation at Io without requiring an unrealistically large Io atmosphere. Thus, at the time the survey magnetometer data was available, the observations were most easily reconciled with a magnetized Io. These results have been described by Kivelson et al. (1996ab) and Linker et al. (1996ab).

(b) Comparison of Models with Significant Mass Loading

When the full particles and fields data for the Io flyby was returned in June 1996, it was apparent that the Io interaction was even more complicated than previously thought. Io was evidently more active than at the time of the Voyager encounter, as the plasma density close to Io (but still far from closest approach) was about a factor of two greater for the Galileo flyby. Waves at the ion gyro-frequency also showed that *significant* ion pickup was occurring, and this was confirmed by the high

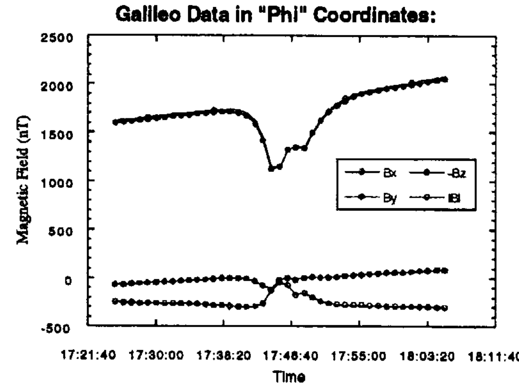

Figure 2 . The Galileo survey magnetometer data. In the "phi" coordinate system, the magnetic field is almost entirely in the -z direction, and x is the corotation direction.

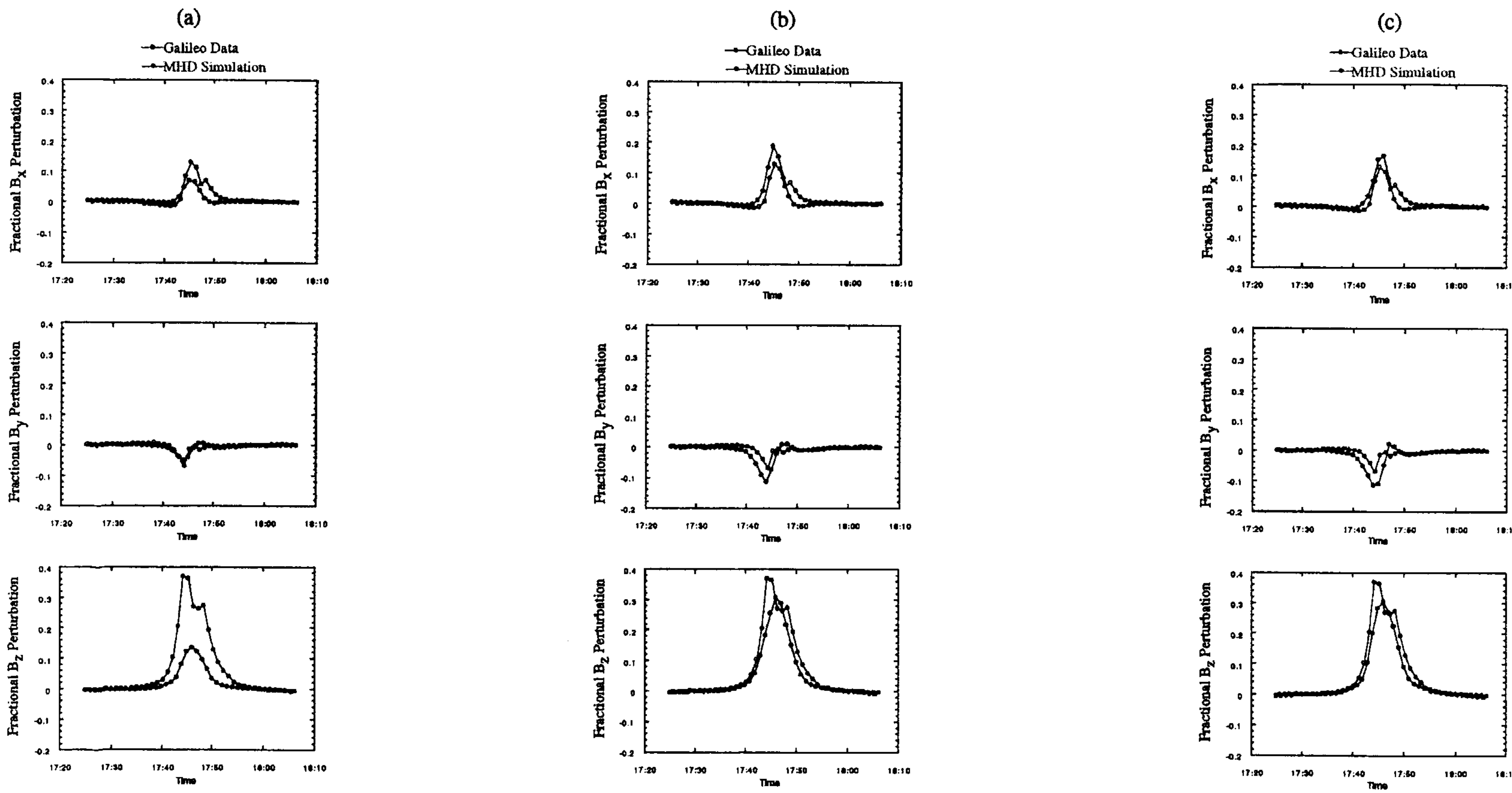

Figure 3. Comparison of the perturbation to the 3 components of the background magnetic field computed from an MHD simulation (blue lines) with Galileo survey magnetometer data (red lines), for 3 different simulations. (a) A conducting Io simulation with 10^{27} ionizations/s in Io's exosphere. This was a typical model based on Voyager observations; it fails to match the large perturbation in B_Z. (b) A conducting model with a radius for the conductor of 1.4 R_{Io}. This is the only conducting model (with modest ion pickup) that can match the B_Z perturbation. The model implies a neutral density > 10^9 at 900 km altitude, which is incompatible with observations of Io's atmosphere and exosphere. (c) A magnetized Io simulation. An Ionian dipole anti-aligned with Jupiter's dipole moment and yielding a surface field at Io's equator of 1300 nT (in the absence of a background field) matches the width and approximate magnitude of the B_z perturbation, with no unusual assumptions about Io's atmosphere.

electron density (approaching 40,000 cm^{-3}) observed near closest approach (Frank et al. 1996; Gurnett et al. 1996). While the change in plasma pressure in the wake alone does not account for the observed magnetic pressure deficit, the higher density in the background plasma raises the background Alfvén Mach number (M_A). As was shown in previous analytic work (Neubauer 1980), larger currents in a conducting Io (and thus a larger B_z perturbation) are possible at higher M_A. The data also suggest that larger amounts of ionization and charge exchange are occurring than we previously considered; these processes produce pickup currents (Goertz 1980) that affect the magnetic field in a manner similar to Pedersen currents in the ionosphere. Taken together, these new observations of the plasma increase the likelihood that an unmagnetized Io could account for the magnetic field observations. Accordingly, we have investigated both magnetized and unmagnetized models of Io where strong ion pickup is occurring. Figure 4 shows the plasma density, velocity, and magnetic field magnitude from a simulation of flow past an unmagnetized Io with the creation of $> 10^{28}$ new ions per second occurring in Io's exosphere. The density and velocity profiles are qualitatively similar to the Galileo observations, with the velocity increasing on Io's flanks, and falling in the center of the wake. The peak density (seen near the center of the wake) is also near the observed value. However, the decrease in $|B|$, while larger than in the cases reported in Figure 2, still does not match the Galileo observations.

Figure 5 shows the results from a simulation of flow past a magnetized Io. Again the plasma parameters are qualitatively similar to the plasma observations, and in this case the magnitude of the decrease in $|B|$ seen in the observations is also present. From these results, we conclude that the Galileo plasma and magnetic field observations are still most easily reconciled with a magnetized model of Io, but further investigation is clearly necessary. For example, while the magnetized model matches the size of the perturbation, the peak in magnitude occurs in the wrong portion of the trajectory, and neither the conducting or the magnetized model matches the asymmetry seen in the magnetic field perturbation. It also remains to be seen whether a level of ionization and charge exchange can be found in the unmagnetized model that provides the observed decrease in $|B|$.

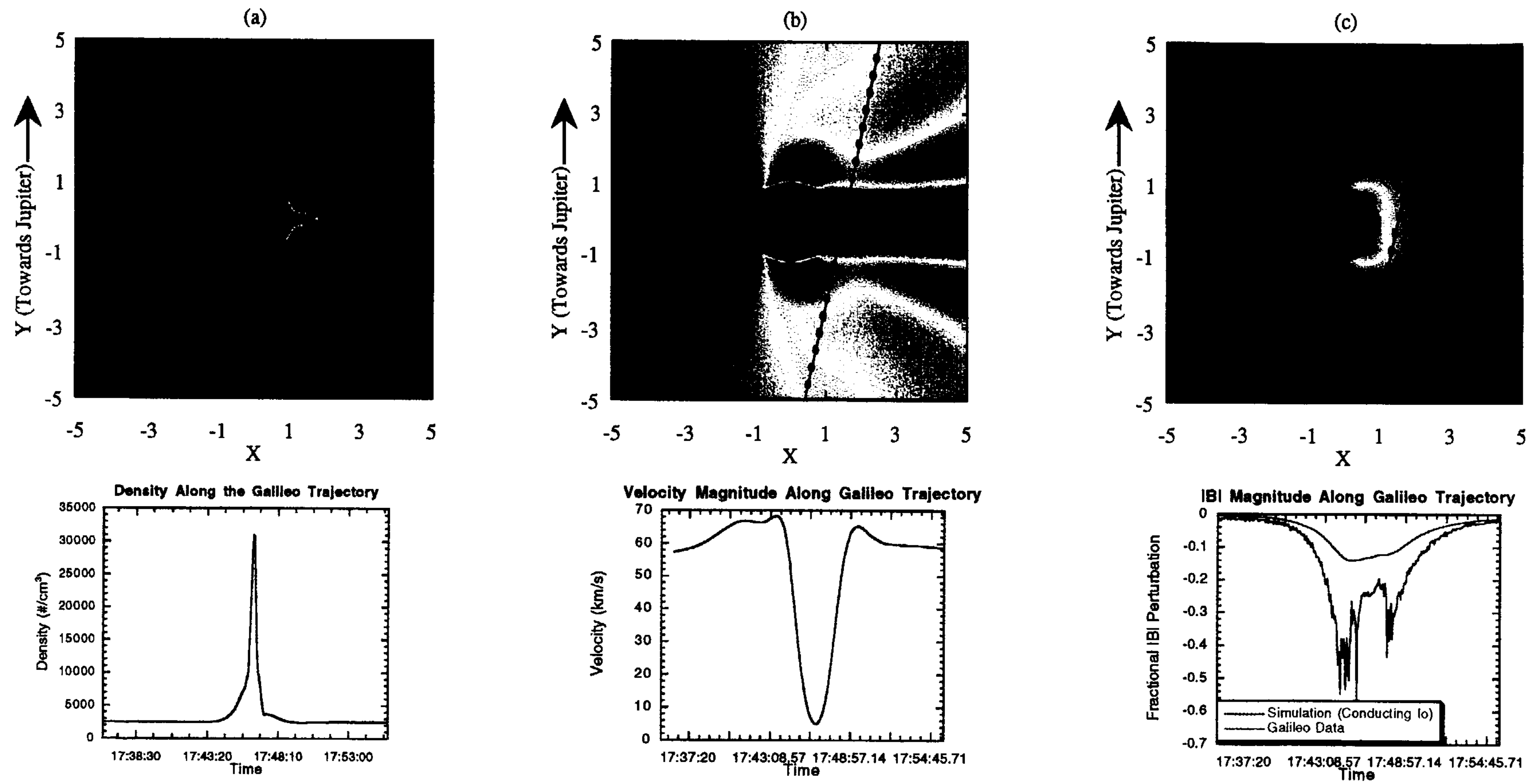

Figure 4. Results for a conducting Io simulation with 2×10^{27} ionizations/s and 1×10^{28} charge exchanges/s, showing (a) the plasma density, (b) the velocity, and (c) the magnetic field. Color contours are shown in the x-z plane (approximately Io's equatorial plane.) A projection of the Galileo trajectory is also shown in this plane, and values extracted from the simulation for a "simulated" flyby through the 3-D data set are also shown. The plasma density and velocity signatures are qualitatively similar to Galileo plasma observations, but the strength of the simulated magnetic perturbation (red line in (c)) is significantly less the observed signature (shown in blue).

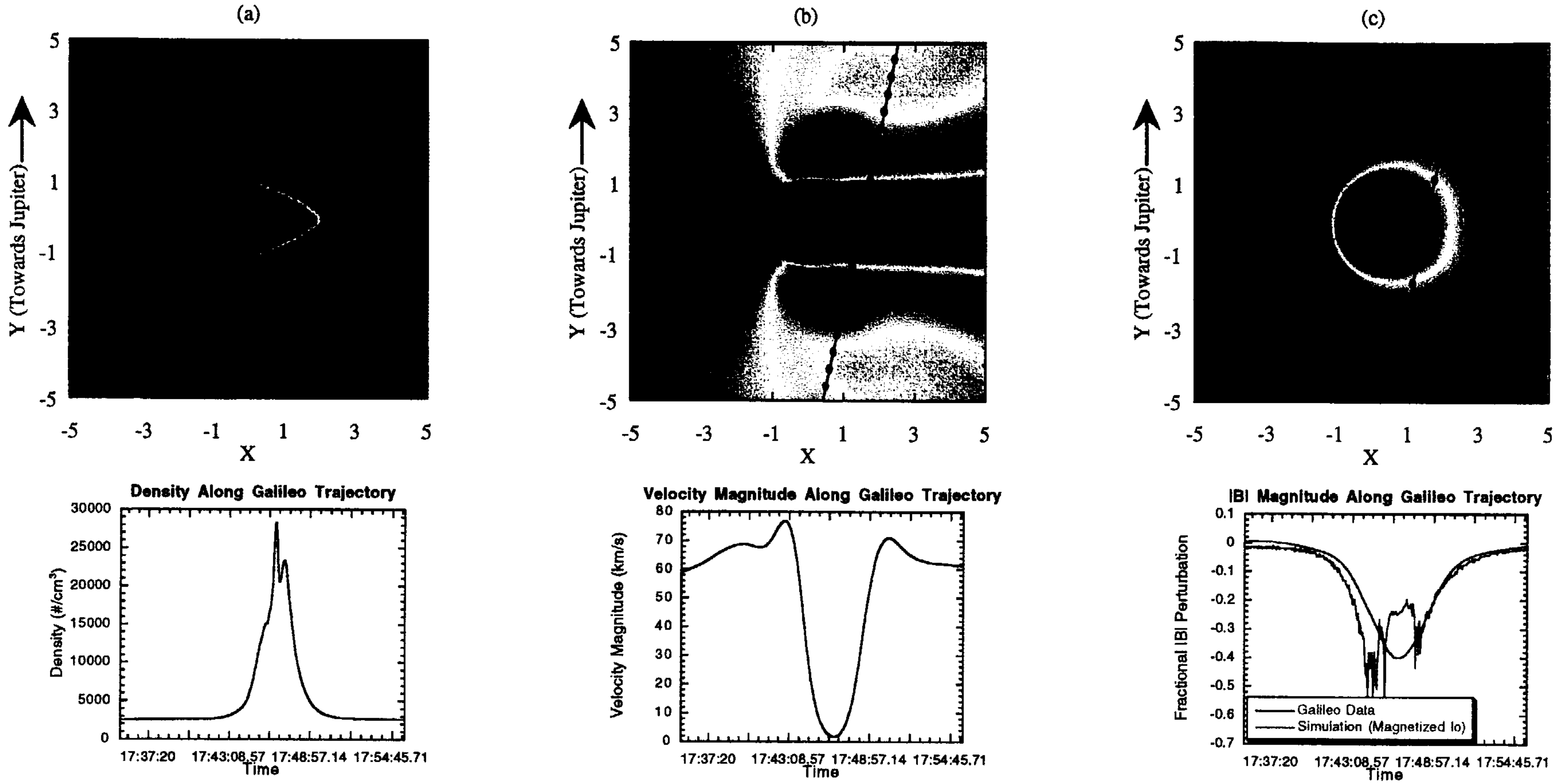

Figure 5. Results for a magnetized Io simulation with 2 x10^{27} ionizations/s, 4.5 x 10^{27} charge exchanges/s, showing (a) the plasma density, (b) the velocity, and (c) the magnetic field. The format is the same as Figure 4. Again, the plasma density and velocity signatures are qualitatively similar to Galileo plasma observations, and for this case the strength of the simulated magnetic perturbation (blue line in (c)) is similar to the observed signature (shown in red). Note the asymmetry in the magnetic signature; thus far none of the models have reproduced this feature.

(c) The Ganymede Interaction

Perhaps the most surprising finding of the Galileo mission thus far is that Ganymede has an intrinsic magnetic field (Kivelson et al. 1996c; Gurnett et al. 1996). We have also begun to investigate this plasma-satellite interaction. Figure 6(a) shows magnetic field tracings from a simulation of plasma flow past a magnetized Ganymede with a dipole moment oriented in the way described by Kivelson et al. (1996c). Figure 6b and 6c show the magnitude of the current density (color contours) with flow vectors (black arrows superimposed). The satellite magnetosphere shows a closed field region bounded by current sheets; the Galileo magnetic field measurements also showed evidence of a current sheet. We plan to use these simulations to analyze data from the two flybys that have already occurred, and to prepare for future flybys later in the mission.

(d) Future Work

In the coming year we plan to continue the work we have described here. In the case of Io, further studies are necessary to understand the presently available data. We plan to investigate solutions with even larger mass loading rates, and we will attempt to constrain the mass loading rate from the data taken along the trajectory. In this regard it is probably important to consider the possibility day-night asymmetry in the neutral density near Io; asymmetric pickup might also help account for the asymmetry in the magnetic perturbation. Our MHD simulations are also being used to select the best trajectory for a possible second flyby of Io; see http://iris023.saic.com:8000/Galileo_comparison/comparison.html for a preliminary comparison.

We also plan continue our investigations of the other Galilean satellites. In our original proposal, we anticipated that these plasma-satellite would likely be similar to the interaction of the solar wind with the Earth's moon. This is apparently the case for Callisto. Preliminary results indicate Callisto has no magnetic field and perturbs the background Jovian field only slightly. The discovery of an intrinsic magnetic field at Ganymede makes this case our primary focus in the coming year. We plan to use our simulations in further analysis of the data already available,

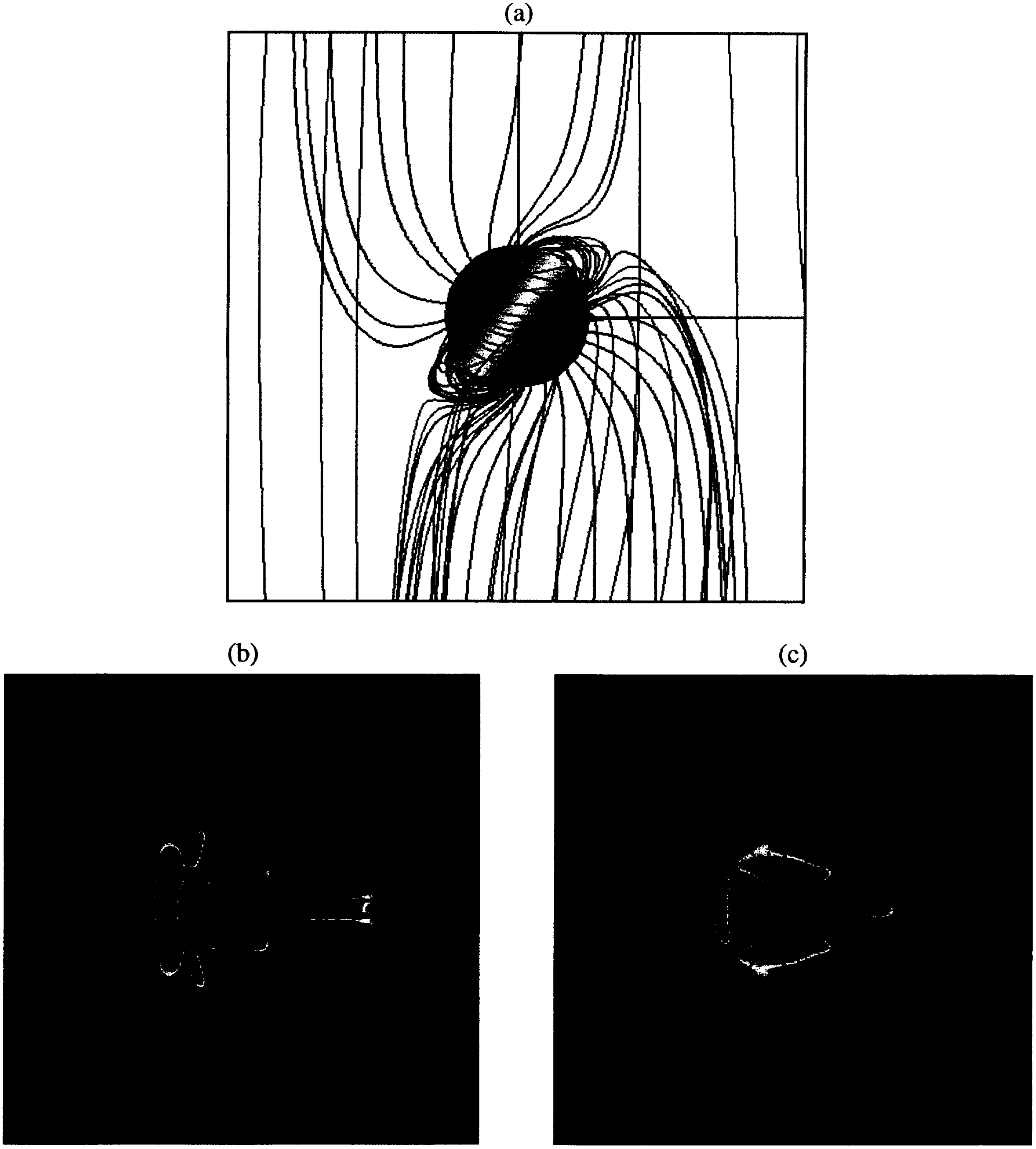

Figure 6. (a) Tracings of the magnetic field from an MHD simulation of plasma flow past Ganymede. (b) Plasma velocity (vectors) and magnitude of the current density (color contours) in the yz plane (plane containing the background magnetic field and the corotation direction). (c) The same as (b) in the xz plane (perpendicular to the background field and the corotation direction). Note that the region of small flow bounded by currents; this is the closed field region.

with the goal of making predictions for the next Ganymede flyby. Of course, the Europa flybys could prove to be extremely interesting as well, so we must anticipate that we will want to model this interaction as well.

(e) Publications and Presentations

Kivelson, M. G., K. K. Khurana, R. J. Walker, C. T. Russell, J. A. Linker, D. J. Southwood, and C. Polanskey, A magnetic signature at Io: Initial Report from the Galileo Magnetometer, *Science*, *273*, 337, 1996a.

Kivelson, M. G., K. K. Khurana, R. J. Walker, J. Warnecke, C. T. Russell, J. A. Linker, D. J. Southwood, and C. Polanskey, Io's interaction with the plasma torus: Galileo magnetometer report, *Science*, *274*, 396, 1996b.

This contract partially or fully supported 2 invited and 5 contributed presentations at scientific meetings in the past year. We also developed a Web page for assessing tours for a possible 2nd flyby of Io at:

http://iris023.saic.com:8000/Galileo_comparison/comparison.html

References

Anderson, J. D., W. L. Sjogren, and G. Schubert, *Science*, *272*, 709, 1996.

Frank, L. A., W. R. Paterson, K. L. Ackerson, V. M Vasyliunas, F. V. Coroniti, and S. J. Bolton, *Science*, *274*, 394, 1996.

Goertz, C. K., *J. Geophys. Res.*,*85*, 2949, 1980.

Gurnett, D. A., W.S. Kurth, A. Roux, S. J. Bolton, and C. F. Kennel, *Science*, *274*, 391, 1996a.

Gurnett, D. A., W.S. Kurth, A. Roux, S. J. Bolton, and C. F. Kennel, *Nature*, in press, 1996b.

Frank, L. A., W. R. Paterson, K. L. Ackerson, V. M Vasyliunas, F. V. Coroniti, and S. J. Bolton, *Science*, *274*, 394, 1996.

Kivelson, M. G., K. K. Khurana, R. J. Walker, C. T. Russell, J. A. Linker, D. J. Southwood, and C. Polanskey, *Science*, *273*, 337, 1996a.

Kivelson, M. G., K. K. Khurana, R. J. Walker, J. Warnecke, C. T. Russell, J. A. Linker, D. J. Southwood, and C. Polanskey, *Science*, *274*, 396, 1996b.

Kivelson, M. G., K. K. Khurana, C. T. Russell, R. J. Walker, J. Warnecke, F. V.

Coroniti, C. Polanskey, D. J. Southwood, and G. Schubert, *Nature*, in press, 1996c.

Kivelson, M. G., J. A. Slavin, and D. J. Southwood, *Science*, *205*, 491, 1979.

Linker, J. A., *Eos. Trans. AGU 76*, F342, Fall AGU meeting, San Francisco, 1995.

Linker, J. A., M. G Kivelson, and R. J. Walker, *Geophys. Res. Lett.*, *15*, 1311, 1988.

Linker, J. A., M. G Kivelson, and R. J. Walker, *J. Geophys. Res.*, *96*, 21037, 1991.

Linker, J. A., M. G. Kivelson, K. K. Khurana, and R. J. Walker, *Eos. Trans. AGU 77*, S174, Spring AGU meeting, Baltimore, 1996a.

Linker, J. A., M. G. Kivelson, K. K. Khurana, and R. J. Walker, *COSPAR*, C3.2, 146, 1996b.

Linker, J. A., L. Bennett, M. G. Kivelson, K. K. Khurana, and R. J. Walker, *Eos. Trans. AGU 77*, F435, Fall AGU meeting, San Francisco, 1996c.

Neubauer, F. M., *Geophys. Res. Lett.*, *5*, 905, 1978.

Neubauer, F. M., *J. Geophys. Res.*, *85*, 1171, 1980.

Schneider, N. M., D. M. Hunten, W. K. Wells, A. B. Schultz, and U. Fink, *Astrophys. J., 368*, 298, 1991.

Schneider, N. M., D. M. Hunten, W. K.

Schubert, G., W. B. Moore, J. D. Anderson, E. L. Lau, and W. L. Sjogren, *Nature*, in press, 1996.

Southwood, D. J., M. G. Kivelson, R. J. Walker, and J. A. Slavin, *J. Geophys. Res.*, *85*, 5959, 1980.

Strobel, D. F., X. Zhu, and M. E. Summers, *Icarus*, *111*, 18, 1994.

Wolf-Gladrow, D. A., F. M. Neubauer, and M. Lussem, *J. Geophys. Res.*, *92*, 1167, 1987.